Charge symmetry breaking in mirror nuclei from quarks

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Abstract

The binding energy differences of the valence proton and neutron of the mirror nuclei, ^{15}O – ^{15}N, ^{17}F – ^{17}O, ^{39}Ca – ^{39}K and ^{41}Sc – ^{41}Ca, are calculated using the quark-meson coupling (QMC) model. The calculation involves nuclear structure and shell effects explicitly. It is shown that binding energy differences of a few hundred keV arise from the strong interaction, even after subtracting all electromagnetic corrections. The origin of these differences may be ascribed to the charge symmetry breaking effects set in the strong interaction through the u and d current quark mass difference.

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The discrepancy between the calculated binding energy differences of mirror nuclei and those measured is a long-standing problem in nuclear physics. It is known as the Okamoto-Nolen-Schiffer (ONS) anomaly [1–3]. Although it was first thought that electromagnetic effects could almost account for the observed binding energy differences, it is now believed that the ONS anomaly has its origin in charge symmetry breaking (CSB) in the strong interaction [4]. In addition to calculations based on charge symmetry violating meson exchange potentials [4–8], a number of quark-based calculations have been performed [9–15] in an attempt to resolve this anomaly. To some extent, these have been stimulated by the discovery of the nuclear dependence of the nucleon structure function measured in deep inelastic lepton-nucleus scattering (the nuclear EMC effect [16]). In such calculations, CSB enters through the up (u) and down (d) current quark mass difference in QCD. Despite these efforts, the difficulty of producing a realistic description of nuclear structure on the basis of explicit quark degrees of freedom has hindered the direct calculation of the binding energy differences. (One such quark-based, nuclear calculation exists [17], but it involved a shell model calculation for the iso-vector mass shifts of iso-spin multiplets in $1s0d$-shell nuclei, and the role of quarks entered through a model for the short-range CSB force.)

In this study we report the results for the binding energy differences of the valence (excess) proton and neutron of the mirror nuclei, ^{15}O – ^{15}N, ^{17}F – ^{17}O, ^{39}Ca – ^{39}K and ^{41}Sc – ^{41}Ca, calculated using a quark-based model involving explicit nuclear structure and shell effects – the quark-meson coupling (QMC) model [18,19]. This model has been successfully applied not only to traditional nuclear problems [18–20] but also to other new areas as well [21]. Although some exploratory QMC results on the ONS anomaly have already been reported [14], an early version of the model was used there, and it was applied to finite nuclei only through local density approximation, rather than a consistent shell model calculation.

A detailed description of the Lagrangian density and the mean-field equations of motion needed to describe a finite nucleus is given in Refs. [18,19]. A major difference in the present work compared with Refs. [18,19] is that here charge symmetry is explicitly broken at the quark level through their masses. We use different values for the u and d current quark masses, and the proton and neutron (effective) masses. Thus, the saturation properties of symmetric nuclear matter needed to be recalculated to fix the relevant quark-meson coupling constants. At position $\vec{r}$ in a nucleus (the coordinate origin is taken at the center of the nucleus), the Dirac equations for the quarks in the proton or neutron bag are given by:

$$\left[i\gamma\cdot\partial_x - \left(\begin{pmatrix} m_u \\ m_d \end{pmatrix} - V^q_\sigma(\vec{r})\right) - \gamma^0\left(V^q_\omega(\vec{r}) \pm \frac{1}{2}V^q_\rho(\vec{r})\right)\right]\begin{pmatrix} \psi_u(x) \\ \psi_d(x) \end{pmatrix} = 0,$$

$$(|\vec{x}-\vec{r}| \leq \text{bag radius}). \tag{1}$$

The mean-field potentials for a bag centered at position $\vec{r}$ in the nucleus are defined by $V^q_\sigma(\vec{r}) = g^q_\sigma\sigma(\vec{r}), V^q_\omega(\vec{r}) = g^q_\omega\omega(\vec{r})$ and $V^q_\rho(\vec{r}) = g^q_\rho b(\vec{r})$, with g^q_σ, g^q_ω and g^q_ρ the corresponding quark and meson-field coupling constants. (Note that we have neglected a possible, very slight variation of the scalar and vector mean-fields inside the nucleon bag due to its finite size [18].) The mean meson fields are calculated self-consistently by solving Eqs. (23) – (30) of Ref. [19] with the proper modifications caused by the different proton and neutron (u and d quark) masses, namely, by solving a set of coupled, non-linear, differential equations for static, spherically symmetric nuclei, resulting from the variation of the effective Lagrangian

density involving the quark degrees of freedom and the scalar, vector and Coulomb fields in mean field approximation. Thus, the present calculation is free from the sort of double counting questioned by Auerbach [22], namely that one should not add the effective mass difference reduction between the proton and neutron in medium on the top of the Coulomb displacement energies. Furthermore, the calculation also includes the shell effects which were discussed by Cohen et al. [23].

Before discussing the results obtained, we need to specify the parameters and inputs used in the calculation. They are summarized in TABLE I. The bag constant, B, is determined by the bare proton mass in free space after allowing for the electromagnetic self-energy correction, $+0.63$ MeV. The parameter z represents the sum of the center-of-mass and gluon fluctuation corrections, included in the standard MIT bag mass formula as $-z/R$ and assumed independent of the density [18]. B and z are determined by setting the bag radius in free space to be $R = 0.8$ fm, and imposing the mass stability condition, $\frac{\partial m_p}{\partial R} = 0$ [18]. (See Ref. [18] for details.) For the neutron, the procedure is the same as that for the proton, allowing for the electromagnetic self-energy correction, -0.13 MeV, but using the values of B and z determined above and calculating the d current quark mass and the bag radius for the neutron by the mass stability condition. Thus, the u current quark mass, m_u, is the basic input parameter used to fix the model parameters so as to reproduce the proton and neutron masses in free space after allowing for the electromagnetic self-energy corrections. The coupling constants, g^q_σ and g^q_ω are determined so as to fit the saturation properties of symmetric nuclear matter – i.e., a binding energy of 15.7 MeV at the saturation density, $\rho_0 = 0.15$ fm^{-3}. The binding energy is calculated by subtracting the average nucleon mass, $(m_p + m_n)/2$, and using the different scalar densities for protons and neutrons. In TABLE I, SU(2) stands for the parameters and inputs obtained and used for the calculation when SU(2) symmetry for the quarks and nucleons is assumed – i.e., using the same values for the u and d quark masses, and also for the proton and neutron masses. We should notice that the coupling constant, g^q_σ, is also scaled for the present calculation of finite nuclei, by the same amount as found necessary in Ref. [19] to fit the r.m.s. charge radius of ^{40}Ca (for the bag radius 0.8 fm) – keeping the ratio (g_σ/m_σ) fixed, because the fixed ratio of (g_σ/m_σ) has no effect on the properties of infinite nuclear matter.

The quark-ρ meson coupling constant, g^q_ρ, needs some explanation. Within QMC, g^q_ρ is determined so as to reproduce the symmetry energy of 35 MeV. However, because the present model does not contain the ρ-nucleon tensor coupling [18,19] and we work only in Hartree approximation [24], this gives an unrealistically large value for the coupling constant, $g^q_\rho = 9.321$. To make a realistic estimate, taking into account the ρ-meson central and spin-orbit potentials for the valence proton and neutron binding energies, we use the phenomenological value, $g^q_\rho = 4.595$ $(g^2_{\rho NN}/4\pi = 4 \times 0.42)$, the value at zero three-momentum transfer corresponding to Hartree approximation, from TABLE 4.1 of Ref. [25]. We also estimate the contributions of the ρ-potentials using the naive QMC value, $g^q_\rho = 9.321$, in order to test the sensitivity.

In FIG. 1 we show the proton and neutron effective mass difference calculated in symmetric nuclear matter, including the electromagnetic self-energy corrections for the proton ($+0.63$ MeV) and neutron (-0.13 MeV). One notices that the proton and neutron mass difference becomes smaller as the baryon density increases – a result which was also found in Refs. [10–12,14]. This seems to work in the right direction to resolve the ONS anomaly,

but it is still not quantitative. (Recall the discussion of Auerbach [22].)

Next, we show the calculated single-particle energies for ^{17}F and ^{17}O in TABLE II, as an example. These mirror nuclei have a common core nucleus, ^{16}O, and have an extra valence proton for ^{17}F and neutron for ^{17}O. In order to focus on the strong interaction effect for the valence proton and neutron, the Dirac equations are solved without the Coulomb and ρ-meson potentials, or the electromagnetic self-energy corrections, and keeping only the charge symmetric σ and ω mean field potentials. Consistently, the valence nucleon contributions are not included in the Coulomb (proton) and ρ-mean field (iso-vector) source densities in the core nucleus. However, for the nucleons in the core nucleus, electromagnetic self-energy corrections and the Coulomb potential as well as the ρ mean field potential are included in addition to the σ and ω mean field potentials in solving the Dirac equations. Results will be shown for three cases for ^{17}F and ^{17}O:

1. Calculation performed imposing charge symmetry breaking through the u and d quark masses and the proton and neutron masses using the phenomenological ρ-quark coupling constant, $g^q_\rho = 4.595$ (at zero three-momentum transfer, $\vec{q} = 0$, corresponding to Hartree approximation [25]) (denoted CSB).

2. Calculation performed assuming SU(2) symmetry for the u and d quark masses and the proton and neutron masses using the phenomenological ρ-quark coupling constant, $g^q_\rho = 4.595$ (denoted SU(2)). (See also the explanation of CSB.)

3. Calculation performed imposing charge symmetry breaking through the different u and d current quark masses and the proton and neutron masses using the ρ-quark coupling constant, $g^q_\rho = 9.321$ (denoted Case 3).

The SU(2) results for ^{17}F and ^{17}O agree perfectly with each other as they should. Single-particle energies in the cores of ^{17}F and ^{17}O are slightly different for both CSB and Case 3. This difference is induced by the different (effective) masses for the valence proton and neutron, arising from the charge and density dependence of their coupling to the self-consistent scalar mean field. This also causes a second order effect on the Coulomb and ρ-meson potentials through the self-consistency procedure. The single-particle energies of the valence proton and neutron are practically equal for both CSB and Case 3.

It is interesting to compare the binding energy differences between the valence proton in ^{17}F and neutron in ^{17}O. Both CSB and Case 3 results give, $E(p)(1d_{5/2}) - E(n)(1d_{5/2}) \simeq 0.18$ MeV, while the SU(2) case is zero as it should be. This amount already shows a magnitude similar to that of the observed binding energy differences, where the origin may be ascribed to the effect of the proton-neutron effective mass difference reduction and simultaneous effect of the core nucleus potentials.

Note that in QMC the quark scalar charge for the d quark, which is defined by the integral of the quark scalar density over the nucleon volume, is slightly greater than that for the u quark, because the u quark mass is smaller than the d quark mass. The lower component of the u quark wave function is enhanced more than that of the d quark. This is a simple consequence of relativistic quantum mechanics. Nevertheless, as a result, the in-medium proton-σ and neutron-σ coupling constants, $g^p_\sigma(\sigma)$ and $g^n_\sigma(\sigma)$, differ from their values in free space and the proton and neutron effective mass difference is reduced [14]. This leads to a reduction in the binding energy differences below the amount one naively

expects from the proton and neutron mass difference of about 2 MeV in free space (without the electromagnetic self-energy corrections) – see also TABLE I and FIG. 1.

The density dependence of the effective $p - n$ mass difference, which we have just described, is the major source of charge symmetry violation discussed here. On the other hand, the fact that there is a small ρ^0 mean field also affects the systematics as we vary A and we now examine this contribution. In FIG. 2 we show the ρ-meson mean field potential generated by the core in ^{17}F and ^{17}O, for CSB and SU(2). There is no distinguishable difference between ^{17}F and ^{17}O for CSB. We will evaluate the ρ-meson central and spin-orbit potential contributions to the single-particle energies of the valence proton and neutron perturbatively. We should note that QMC gives the correct expression for the spin-orbit potentials, including the finite size of the nucleon [18,20]:

$$V^{s.o.}(r)\vec{l}\cdot\vec{s} = \frac{-1}{2m_N^{*2}(r)r}\left[\Delta_\sigma + 3(1-2\mu_s\eta(r))\Delta_\omega + \frac{1}{2}\tau_3^N(1-2\mu_v\eta(r))\Delta_\rho\right]\vec{l}\cdot\vec{s}. \tag{2}$$

We are interested in the last term in Eq. (2), the ρ-meson spin-orbit potential, which gives opposite contributions for the valence proton and the valence neutron. Contributions from the other mesons to Eq. (2) have the same sign for protons and neutrons and their contributions to the binding energy differences are therefore expected to be tiny. Furthermore, the contribution from the effective mass difference of the proton and neutron is even higher order. Thus, we use the SU(2) value for m_N^{*2} in Eq. (2) to evaluate the ρ-meson spin-orbit potential. Using the calculated wave functions for the valence proton and neutron, obtained by solving the Dirac equations without the Coulomb and ρ-meson potentials or the electromagnetic self-energy corrections, we evaluate the ρ-meson contributions perturbatively:

$$\delta E_\rho = \int d^3r\, \psi^\dagger_{valence}(\vec{r})\, [\frac{1}{2}\tau_3^N V_\rho(r)]\, \psi_{valence}(\vec{r}), \tag{3}$$

$$\delta E_\rho^{s.o.} = \int d^3r\, \psi^\dagger_{valence}(\vec{r})\, [\frac{1}{2}\tau_3^N V_\rho^{s.o.}(r)]\, (\vec{l}\cdot\vec{s})\, \psi_{valence}(\vec{r}), \tag{4}$$

where $1/2V_\rho(r)$ is shown in FIG. 2, and $V_\rho^{s.o.}(r) = \frac{-1}{2m_N^{*2}(r)r}(1-2\mu_v\eta(r))\Delta_\rho$, the third term in Eq. (2). In QMC the iso-vector magnetic moment, μ_v, is calculated to be $\mu_v^{QMC} = 2.558$ for the bag radius $R = 0.8$ fm. This is somewhat smaller than the empirical value, $\mu_v^{emp.} = 4.7051$. Thus, for the CSB and SU(2) calculations, we use the empirical value, $\mu_v^{emp.} = 4.7051$, together with the phenomenological coupling constant, $g_\rho^q = 4.595$, in order to make a more realistic estimate.

In TABLE III we summarize the calculated single-particle energies for the valence proton and neutron of the mirror nuclei for two cases, CSB and SU(2). We expect that the results for CSB are the more realistic.

Comparing the ρ-potential contributions for the hole states with core plus valence states, one notices the shell effects due to the ρ-potentials. The ρ-potential contributions for the discrepancies of the ^{15}O – ^{15}N and ^{17}F – ^{17}O binding energy differences are about -0.11 MeV and -0.011 MeV, respectively, while for the ^{39}Ca – ^{39}K and ^{41}Sc – ^{41}Ca cases, they are about -0.17 MeV and -0.013 MeV, respectively. These results reflect the difference in the shell structure, namely hole states tend to have larger ρ-potential contributions than the core plus valence nucleon states. This can be understood because, in the hole states,

the excess proton or neutron sits in the region where the iso-vector density distribution is larger.

For the SU(2) case, the valence state binding energy differences of mirror nuclei, δE, come entirely from the ρ-meson potentials. We see that δE obtained in CSB is always larger than that for SU(2). Typical values for the binding energy differences are a few hundred keV.

The larger binding energy differences for the valence proton and neutron obtained in CSB indicate that the prime CSB effects originate in the u-d current quark mass difference. The resulting contribution to the binding energy differences is of the order of about a few hundred keV. This is precisely the order of magnitude which is observed as the ONS anomaly [3,4]. Furthermore, as we see from TABLE III, the systematic dependence on A is also reasonably well described, except for the ^{39}Ca – ^{39}K case. It is a fascinating challenge for the future to compare this result with the traditional mechanism involving $\rho - \omega$ mixing [5]. This will involve the issue of the possible momentum dependence of the $\rho - \omega$ mixing amplitude [26,4]. In addition, one would need to examine whether there is any deeper connection between these apparently quite different sources of charge symmetry violation.

We would like to stress that the present contribution to the ONS anomaly is based on a very simple but novel idea, namely the slight difference between the quark scalar densities of the u and d quarks in a bound nucleon, which stems from the u and d quark mass difference [14]. Our results were obtained within an explicit shell model calculation, based on quark degrees of freedom. They show that if charge symmetry breaking is set through the u and d current quark mass difference so as to reproduce the proton and neutron masses in free space (without any electromagnetic interaction effects), it produces binding energy differences for the valence (excess) proton and neutron of mirror nuclei of a few hundred keV. The origin of this effect within relativistic quantum mechanics is so simple that it is natural to conclude that a sizable fraction of the charge symmetry breaking in mirror nuclei arises from the density dependence of the u and d quark scalar densities in a bound nucleon.

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TABLES

TABLE I. Inputs, parameters and some of the quantities calculated in the present study. The quantities with a star, *, are those quantities calculated at normal nuclear matter density, $\rho_0 = 0.15$ fm^{-3}. The d current quark mass, m_d, is calculated in the model so as to reproduce the neutron mass, $m_n = 939.6956$ MeV, in free space. Phenomenological ρ-quark coupling constant, g_ρ^q (phen.) ($g_{\rho NN}^2/4\pi = 4 \times 0.42$), the value at zero three-momentum transfer corresponding to Hartree approximation, is taken from TABLE 4.1 of Ref. [25].

	m (MeV)	R (fm)	$B^{1/4}$ (MeV)	z	m^* (MeV)	R^* (fm)
p (CSB)	937.6423 (input)	0.8 (input)	169.81	3.305	751.928	0.7950
n (CSB)	939.6956 (input)	0.8000	169.81	3.305	753.597	0.7951
N (SU(2))	939.0 (input)	0.8 (input)	169.97	3.295	754.542	0.7864
	m_u (MeV)	m_d (MeV)	g_σ^q	g_ω^q	g_ρ^q (QMC)	g_ρ^q (phen.)
CSB	5.0 (input)	9.2424	5.698	2.744	9.321	4.595
SU(2)	5.0 (input)	5.0 (input)	5.685	2.721	9.330	4.595

TABLE II. Calculated single-particle energies (in MeV) for ^{17}F and ^{17}O. For CSB and SU(2) the phenomenological value, $g_\rho = 4.595 = g_\rho^q = g_{\rho NN}$ is used, while for Case 3, $g_\rho = 9.321$, the value determined in QMC is used. For the valence proton and neutron the Dirac equations are solved without including the Coulomb and ρ-meson potentials or the electromagnetic self-energy corrections.

	CSB		SU(2)		Case 3	
	^{17}F	^{17}O	^{17}F	^{17}O	^{17}F	^{17}O
p $1s_{1/2}$	-28.800	-28.805	-28.663	-28.663	-28.991	-28.996
$1p_{3/2}$	-14.154	-14.158	-14.032	-14.032	-14.248	-14.251
$1p_{1/2}$	-12.495	-12.499	-12.383	-12.383	-12.589	-12.592
n $1s_{1/2}$	-33.367	-33.372	-32.967	-32.967	-33.168	-33.173
$1p_{3/2}$	-18.259	-18.263	-17.918	-17.918	-18.159	-18.163
$1p_{1/2}$	-16.587	-16.590	-16.258	-16.258	-16.487	-16.490
valence	p	n	p	n	p	n
$1d_{5/2}$	-3.918	-4.099	-3.848	-3.848	-3.918	-4.100

TABLE III. Calculated single-particle energies (in MeV) of mirror nuclei. δE_ρ, and $\delta E_\rho^{s.o.}$ stand for the contributions from the ρ-meson central and spin-orbit potentials of the core nucleus, respectively. (See also Eqs. (3) and (4).) The valence proton or neutron is indicated inside brackets. The discrepancies between the experimental values and the theoretical expectations in the absence of charge symmetry violating strong interactions, are taken from TABLE II of Ref [8], by averaging over the theoretical values. For the other explanations see the caption of TABLE II.

	CSB		SU(2)	
	^{15}O(p)	^{15}N(n)	^{15}O(p)	^{15}N(n)
$1p_{3/2}$	-14.397	-14.631	-14.306	-14.306
δE_ρ	-0.046	0.047	-0.040	0.040
$\delta E_\rho^{s.o.}$	-0.009	0.009	-0.008	0.008
Total	-14.452	-14.575	-14.353	-14.258
$\delta E = E(p) - E(n)$	$\delta E =$	0.123	$\delta E =$	-0.095
	observed =	0.227		
	^{17}F(p)	^{17}O(n)	^{17}F(p)	^{17}O(n)
$1d_{5/2}$	-3.918	-4.099	-3.848	-3.848
δE_ρ	-0.011	0.011	-0.009	0.009
$\delta E_\rho^{s.o.}$	0.006	-0.006	0.005	-0.005
Total	-3.923	-4.094	-3.852	-3.843
$\delta E = E(p) - E(n)$	$\delta E =$	0.171	$\delta E =$	-0.009
	observed =	0.218		
	^{39}Ca(p)	^{39}K(n)	^{39}Ca(p)	^{39}K(n)
$1d_{3/2}$	-16.407	-16.689	-16.332	-16.332
δE_ρ	-0.071	0.072	-0.065	0.065
$\delta E_\rho^{s.o.}$	-0.016	0.016	-0.015	0.015
Total	-16.493	-16.601	-16.411	-16.252
$\delta E = E(p) - E(n)$	$\delta E =$	0.108	$\delta E =$	-0.159
	observed =	0.340		
	^{41}Sc(p)	^{41}Ca(n)	^{41}Sc(p)	^{41}Ca(n)
$1f_{7/2}$	-6.970	-7.210	-6.900	-6.900
δE_ρ	-0.018	0.018	-0.016	0.016
$\delta E_\rho^{s.o.}$	0.012	-0.012	0.011	-0.011
Total	-6.976	-7.204	-6.905	-6.894
$\delta E = E(p) - E(n)$	$\delta E =$	0.228	$\delta E =$	-0.011
	observed =	0.463		

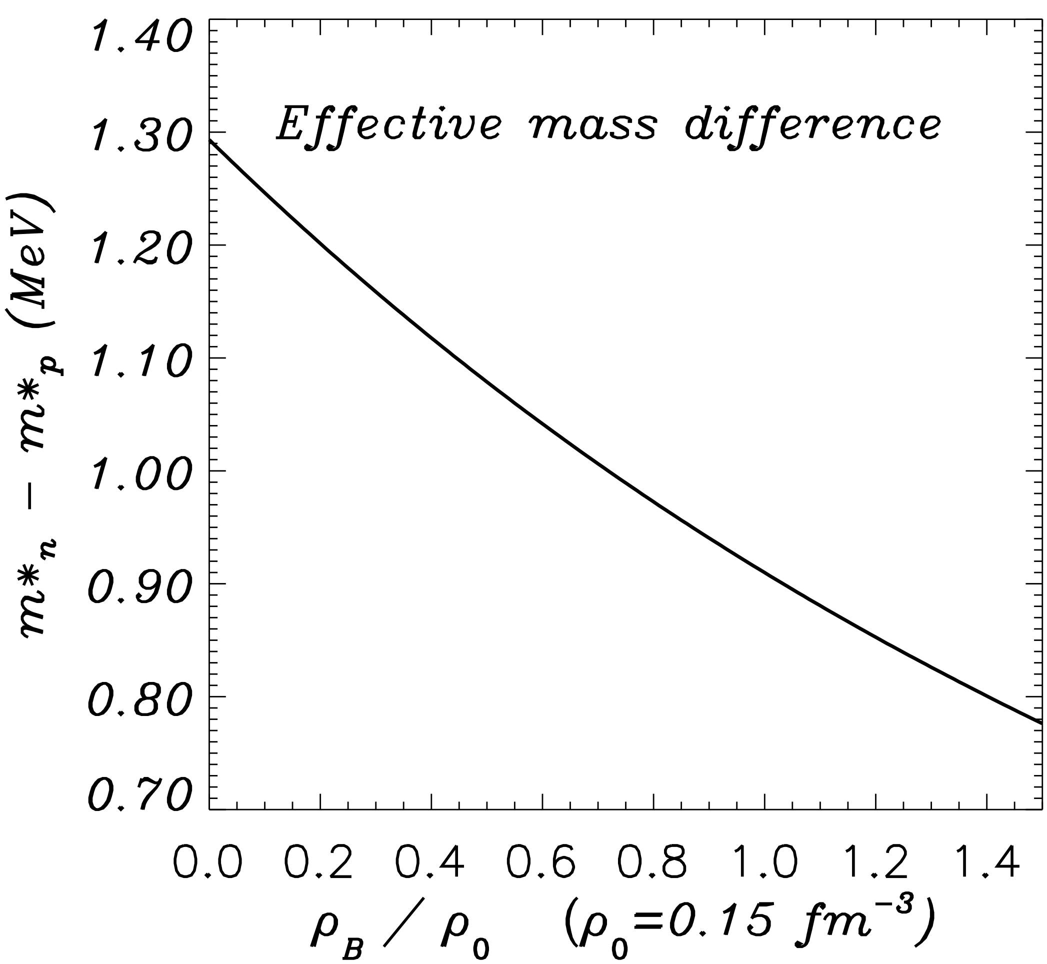

FIG. 1. Proton-neutron effective mass difference in symmetric nuclear matter with the electromagnetic self-energy corrections.

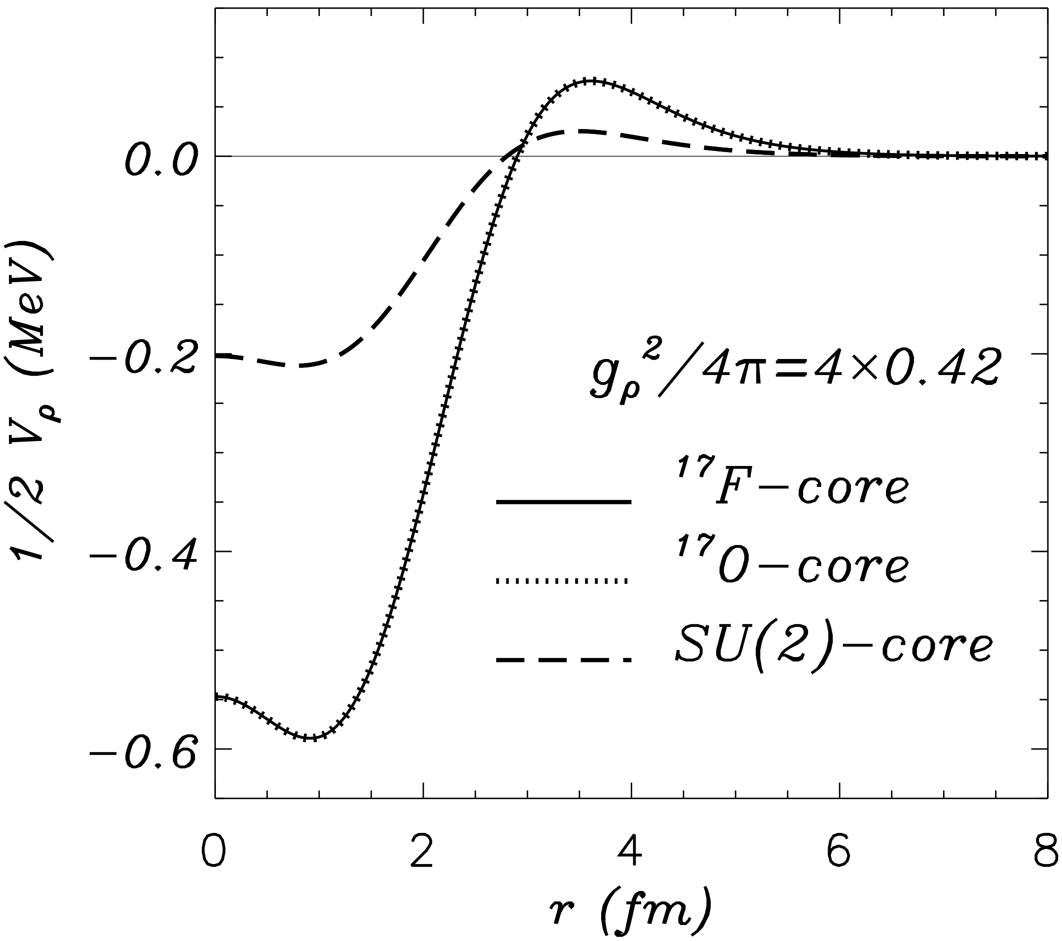

FIG. 2. Calculated ρ-meson (iso-vector) mean field potential generated by the core in ^{17}O and ^{17}F, for CSB and SU(2).